

# $(m, n)$ -relaying for OFDMA Cellular Networks

Von der Fakultät für Elektrotechnik, Informationstechnik, Physik der  
Technischen Universität Carolo-Wilhemina zu Braunschweig

zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.)

genehmigte

Dissertation

von

Dott. Mag. Ing. Tommaso Balercia

geboren in Jesi

Eingereicht am:	14. Januar 2013
Mündliche Prüfung am:	27. September 2013
Berichterstatter:	Prof. Dr.-Ing. Thomas Kürner
Mitberichterstatter:	Prof. Dr.-Ing. Erik Fledderus
Vorsitzender:	Prof. Dr.-Ing. Ulrich Reimers



Mitteilungen aus dem Institut für Nachrichtentechnik der  
Technischen Universität Braunschweig

Band 33

**Tommaso Balercia**

**(m,n)-relaying for OFDMA Cellular Networks**

Shaker Verlag  
Aachen 2014

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Braunschweig, Techn. Univ., Diss., 2013

Copyright Shaker Verlag 2014

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-2713-6

ISSN 1865-2484

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

## Zusammenfassung

Die Spektral-Effizienz des Systems von modernen, zellularen Kommunikations-Netzen ist in erster Linie durch die Interferenz zwischen den Übertragungskanälen (Inter-Channel Interference, ICI) limitiert. Die Vermeidung von Interferenzen ist seit der Einführung komplexer Übertragungsmechanismen, die eine gezielte Nutzung der räumlichen Eigenschaften der Übertragungskanäle erlauben, immer mehr in den Fokus intensiver Forschung gerückt. Dabei entspricht der Ansatz der Kooperation zwischen Basis-Stationen (Base Station Cooperation, BSC) dem derzeitigen Stand der Technik und Wissenschaft, wie in der aktuellen Literatur beschrieben.

BSC nutzt sogenannte Multi-User Multiple-Input Multiple-Output (MU-MIMO) Kanäle zwischen den zellularen Basis-Stationen und den Endgeräten. BSC kann de facto als asymmetrischer Ansatz zur ICI-Vermeidung gesehen werden. In diesem Zusammenhang bedeutet asymmetrisch, dass der benötigte Rechenaufwand zur ICI-Vermeidung fast ausschließlich auf der Infrastruktur-Seite liegt, während die Endgeräte unverändert weiter betrieben werden können. Es ist offensichtlich, dass diese Eigenschaft von BSC von großem praktischen Vorteil ist, da zusätzliche Komplexität in den Endgeräten soweit wie möglich vermieden wird. Ein Nachteil dieser Technologie liegt allerdings darin, dass die zellularen Basis-Stationen durch kostenaufwendige Backhaul-Netzwerke miteinander verknüpft werden müssen.

Diese Dissertation knüpft an ähnliche Betrachtungen an, geht aber weiter und analysiert und entwickelt einen neuen asymmetrischen Ansatz zur ICI-Vermeidung, der kein neues Backhaul-Netzwerk mehr benötigt. Dieser neue Ansatz wird im folgenden  $(m, n)$ -Relaying genannt. Hierbei werden Relais-Knoten so installiert, dass sie mit mehreren zellularen Basis-Stationen gleichzeitig kommunizieren können, und MU-MIMO Kanäle zwischen den Zellen gezielt ausgenutzt werden. Der Hauptvorteil dieses neuen Ansatzes liegt darin, dass der Kommunikationsaufbau ohne jeglichen Datenaustausch zwischen den Zellen erfolgt.

Desweiteren wurde die Umsetzung dieses neuen Ansatzes im Rahmen dieser Dissertation auf Orthogonal Frequency-Division Multiple Access (OFDMA) Netzwerke zugeschnitten, da diese Technologie derzeit weit verbreitet ist. Zusätzlich konzentriert sich dieses Dokument auf genau die OFDMA Netze, in denen alle zellularen Basis-Stationen und Endgeräte mit nur einer Antenne ausgestattet sind. Ein deterministisches Kanal-Modell, dessen Komplexität bewußt auf diese Aufgabe zugeschnitten wurde, wird in der entsprechenden System-Analyse genutzt. Die im Rahmen dieser Dissertation erzielten Ergebnisse zeigen, dass der neue  $(m, n)$ -Relaying-Ansatz für eine effiziente Vermeidung von ICI geeignet ist.



## Abstract

The system spectral efficiency of modern cellular networks is primarily limited by the presence of inter-channel interference (ICI). With the introduction of sophisticated transmission techniques capable of exploiting the spatial characteristics of the propagation channel, the mitigation of ICI has become an area of intense research. Among the approaches that were proposed, a powerful class of techniques known in literature as base station cooperation (BSC) can be regarded as the current state of the art.

Based on the establishment of inter-cell multi-user multiple input multiple output (MU-MIMO) channels between base stations and terminals, BSC is an asymmetric paradigm to ICI mitigation. The term asymmetric indicates that the complexity required to address the ICI is allocated entirely to the infrastructure, while the terminals need no modification. As can be easily inferred, this is an appealing trait of BSC. What cannot, however, be regarded as such is the fact that BSC requires to interconnect groups of base stations by means of expensive backhaul networks.

Moving from similar observations, this dissertation aims at introducing and analysing a new asymmetric approach to ICI mitigation that requires no backhaul network:  $(m, n)$ -relaying. Based on the deployment of shared relay nodes, the novel paradigm also relies on the establishment of inter-cell MU-MIMO channels. Its design, however, allows for such an establishment to occur without any exchange of information between the cells.

Due to the technological relevance of such systems, the mechanisms that define  $(m, n)$ -relaying are here presented in the context of orthogonal frequency-division multiple access (OFDMA) networks. In particular, the treatise focuses on those OFDMA networks in which all base stations and all terminals are equipped with a single antenna. As for the performance characterising the paradigm, its analysis was conducted using a deterministic propagation model whose complexity was specifically tailored for the task. The derived results indicate that, for the forward traffic,  $(m, n)$ -relaying is an effective approach to ICI mitigation.





## Acknowledgements

This dissertation is the result of several years spent at Comneon GmbH (now part of Intel Mobile Communications or IMC) as a doctoral candidate. I would thus like to start by thanking IMC for financing my activities and for giving me the freedom that I always enjoyed. Among the numerous colleagues that I had the privilege to work with, here I would like mention Dr. Markus Mück, Dr. Valerio Frascolla and Dr. Christian Rom for their support and for everything they taught me.

Towards my advisor, Prof. Thomas Kürner, I would like to express all my gratitude for his friendly and insightful guidance. I'm also grateful to Prof. Erik Fledderus for being my second advisor, to Prof. Danilo Erricolo for his valuable advices and to Prof. Ulrich Reimers for serving as the head of the committee.

Special thanks go finally to Susanne Kuhn for proofreading parts of the manuscript, and to my family and friends for their incessant support.



# Contents

List of Figures	xii
List of Tables	xiii
List of Acronyms	xv
<b>1 Introduction</b>	<b>1</b>
1.1 Scope . . . . .	2
1.2 Outline . . . . .	3
<b>2 ICI reduction</b>	<b>5</b>
2.1 Base station cooperation . . . . .	5
2.1.1 Forward link . . . . .	7
2.1.2 Backward link . . . . .	12
2.2 $(m, n)$ -relaying . . . . .	15
2.2.1 Forward link . . . . .	17
2.2.2 Backward link . . . . .	21
2.2.3 Hierarchical $(m, n)$ -relaying . . . . .	21
<b>3 OFDMA systems</b>	<b>25</b>
3.1 Standard systems . . . . .	25
3.2 Systems employing base station cooperation . . . . .	29
3.3 Systems employing $(3, 6\kappa)$ -relaying . . . . .	34
3.3.1 $(3, 6)$ -relaying . . . . .	35
3.3.2 $(3, 18)$ -relaying . . . . .	39
<b>4 Simulation models</b>	<b>43</b>
4.1 Modelling rationale . . . . .	44
4.2 Propagation . . . . .	56
4.2.1 Accuracy and complexity . . . . .	69
4.3 Mobility . . . . .	77

<b>5</b>	<b>Numerical Analysis</b>	<b>83</b>
5.1	Base station cooperation . . . . .	87
5.2	$(3, 6\kappa)$ -relaying . . . . .	90
<b>6</b>	<b>Conclusion and future work</b>	<b>101</b>
<b>A</b>	<b>Pareto-optimal ZF beamforming</b>	<b>103</b>
<b>B</b>	<b>FA allocation strategies for BSC</b>	<b>107</b>
<b>C</b>	<b>Diffraction from dielectric wedges</b>	<b>111</b>
	<b>Bibliography</b>	<b>116</b>

# List of Figures

2.1	A possible approach to divide the network into cooperative sets of base stations. . . . .	6
2.2	A cooperative set of base stations transmitting to a group of mobile stations. . . . .	7
2.3	A cooperative set of base stations receiving from a group of mobile stations. . . . .	12
2.4	The state space of the transmission context portrayed in Fig. 2.3 . . . . .	15
2.5	The introduction of a third entity allows to reduce the ICI without any coordination between either the transmitters or the receivers. . . . .	16
2.6	Interferers in a relay-augmented network designed according to the hexagonal model. . . . .	18
2.7	A set of adjacent primary stations transmitting to a group of mobile stations through a secondary station. . . . .	18
2.8	A set of adjacent primary stations receiving from a group of mobile stations through a secondary station. . . . .	21
2.9	A set of adjacent primary stations and its associated hierarchical relay station. . . . .	22
2.10	Exchange of cooperative information for BSC and hierarchical $(m, n)$ -relaying. . . . .	24
3.1	Multiplexing strategies for a base station belonging respectively to an OFDM and an OFDMA cellular system. . . . .	26
3.2	The enforcement of BSC for a network allocating resources like a standard system. . . . .	30
3.3	The fractional frequency reuse scheme for BSC. . . . .	31
3.4	Temporal evolution of the frequency reuse scheme illustrated in Fig. 3.3. . . . .	33
3.5	Associative and serving strategies for $(3, 6)$ -relaying. . . . .	35
3.6	Associative and serving strategies for $(3, 18)$ -relaying. . . . .	39
3.7	$(3, 18)$ -relaying and hierarchical $(3, 18)$ -relaying. . . . .	41
4.1	The urban environment used for the analysis. . . . .	45

4.2	Results of a set of simulations aiming at defining the value of $N_{\text{MS}}^{(2)}$ .	49
4.3	The trend of $\mathcal{B}^{(f)}$ when the channels are calculated with the WINNER models.	55
4.4	The propagation planes considered by the tracer.	59
4.5	The steps in the creation of the vertical visibility graph.	60
4.6	A ray along the vertical plane.	61
4.7	The steps in the creation of the lateral visibility graph.	62
4.8	Keller's diffraction cone for a field impinging on a wedge.	63
4.9	Reflection from a surface.	64
4.10	Diffraction from a single wedge.	65
4.11	Total field for the scenario in Fig. 4.10.	67
4.12	Diffraction from a pair of joined wedges.	68
4.13	Total field for the scenario in Fig. 4.12.	70
4.14	The domain within which lateral rays are searched for.	72
4.15	Routes and transmitter with respect to which the measurements were taken.	74
4.16	The steps in the creation of the mobility domain.	78
4.17	The derivation of crossings for the specific case of crossroads.	79
4.18	Trend of the function $f(d)$ with respect to the distance $d$ .	82
5.1	The primary infrastructure and the population of terminals considered in the study.	84
5.2	Terminals to be served per cell or cooperative set.	85
5.3	Scenario for BSC.	88
5.4	ACD of the transferred bits for BSC.	89
5.5	Scenario for (3, 6)-relaying.	91
5.6	ACD of the transferred bits for (3, 6)-relaying.	92
5.7	Scenario for hierarchical (3, 6)-relaying.	93
5.8	ACD of the transferred bits for hierarchical (3, 6)-relaying.	94
5.9	Scenario for (3, 18)-relaying.	96
5.10	ACD of the transferred bits for (3, 18)-relaying.	97
5.11	Scenario for hierarchical (3, 18)-relaying.	98
5.12	ACD of the transferred bits for hierarchical (3, 18)-relaying.	99
B.1	ACD of the transferred bits for BSC.	109
C.1	Diffraction from a single wedge.	112
C.2	Trend of the term $r(\phi', \phi)$ .	113

# List of Tables

4.1	Number of solved mathematical programs. . . . .	52
4.2	Optimal electromagnetic parameters. . . . .	76
4.3	First and second moment of the error. . . . .	77
5.1	Antenna parameters. . . . .	86
5.2	Simulation parameters. . . . .	87
5.3	Ratios between the medians for (3,6)-relaying. . . . .	91
5.4	Ratios between the medians for hierarchical (3,6)-relaying. . . . .	95
5.5	Ratios between the medians for (3,18)-relaying. . . . .	96
5.6	Ratios between the medians for hierarchical (3,18)-relaying. . . . .	98
5.7	Ratios between the average power used by a system based on (3,6 $\kappa$ )-relaying and a standard one for the forward traffic. . . . .	100
C.1	Optimal electromagnetic parameters. . . . .	114
C.2	First and second moment of the error. . . . .	114
C.3	Optimal electromagnetic parameters. . . . .	115
C.4	First and second moment of the error. . . . .	115





# List of Acronyms

ACD	approximate cumulative distribution
AS	asymmetric scenario
BS	base station
BSC	base station cooperation
CFR	channel frequency response
CPG	channel power gain
CSI	channel state information
DPC	dirty paper coding
DSB	diffraction shadow boundary
FA	fully adaptive
FDD	frequency division duplexing
ICI	inter-channel interference
ISB	incident shadow boundary
LOS	line-of-sight
MMSE	minimum mean square error
MS	mobile station
MU-MIMO	multi-user multiple input multiple output
NLOS	non-line-of-sight
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
PA	partially adaptive

PEC	perfect electrical conductor
RRH	remote radio head
RS	relay station
RSB	reflection shadow boundary
RWP	random way-point
SIC	successive interference cancellation
SINR	signal to interference plus noise ratio
SOCP	second order cone program
SS	symmetric scenario
SSE	system spectral efficiency
TDD	time division duplexing
UTD	uniform geometrical theory of diffraction
ZF	zero forcing